Development of a New Unmanned Semi-Submersible (USS) Vehicle

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Abstract* - C&C Technologies in Lafayette, LA in cooperation with the Naval Research Laboratory (NRL) Mapping, Charting and Geodesy Branch at Stennis Space Center, MS and Autonomous Surface Vehicles, Ltd. in W. Sussex, UK, is implementing a multiyear development program of an Unmanned Semi-Submersible (USS) vehicle. Originally sponsored by the National Oceanic and Atmospheric Administration (NOAA), the goal of this project is to develop an unmanned, compact, rugged, and high-endurance vehicle capable of acquiring sensor based measurements and yielding higher coverage rates per day in sea states beyond those possible with a small manned conventional survey boat. Furthermore, the USS will facilitate an evaluation of the full potential of a rugged semi-submersible as a low cost force multiplier for littoral mapping purposes in both commercial and military applications. Vehicle attributes include a notable sea-keeping capability that offers promise for nautical charting surveys, military applications, and homeland defense programs. This program builds upon earlier NRL research with the unmanned semi-submersible survey prototype, ORCA (Oceanographic Remotely Controlled Automaton) to support the Naval Oceanographic Office (NAVOCEANO). The ORCA was an air-breathing vessel with a majority of its structure traveling just below the water surface. The ORCA's radio antennae were affixed to a snorkel, which allowed for remote vehicle command and control in addition to real-time data transfer. The ORCA also used Differential Global Positioning System (DGPS) for precise positioning. In a similar fashion, the newly developed USS navigates submerged with only a narrow sail structure extending above the waterline. The USS design criteria are based upon the maximum integration of readily available Commercial Off The Shelf (COTS) hardware and instrumentation acquired largely from small boat technology. Requirements mandate a form factor suitable for stern ramp launch and retrieval, the capacity to operate dockside without special equipment, a re-configurable payload capability, a survey speed of at least six knots, and an endurance of at least two days. Overall vehicle height is restrained to allow for safe maintenance work on the deck of a moving ship and to accommodate shipping and storage within standard ISO containers. The USS program is aimed to provide risk reduction to support the Navy Unmanned Underwater Vehicle (UUV) Master Plan by evaluating new sensors, modularity, commonality of equipment, and experimentation with UUV systems. This paper discusses the USS concept, the decision making process, program milestones, and the vehicle design process including establishment of the performance criteria, hydrodynamic model testing, computer simulation, manufacture, and sea testing results.

Project Goals

The primary goal of the USS project is to develop a new vehicle which performs better than a survey launch. A survey launch is a boat, usually six to ten meters long, which is used to carry hydrographic survey sonars. The boat is launched and recovered daily from a mother ship. Launches are usually operated only in daylight for safety and to allow time for the crew

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14. ABSTRACT

C&C Technologies in Lafayette, LA in cooperation with the Naval Research Laboratory (NRL) Mapping, Charting and Geodesy Branch at Stennis Space Center, MS and Autonomous Surface Vehicles, Ltd. in W. Sussex, UK, is implementing a multiyear development program of an Unmanned Semi-Submersible (USS) vehicle. Originally sponsored by the National Oceanic and Atmospheric Administration (NOAA), the goal of this project is to develop an unmanned, compact, rugged, and highendurance vehicle capable of acquiring sensor based measurements and yielding higher coverage rates per day in sea states beyond those possible with a small manned conventional survey boat. Furthermore, the USS will facilitate an evaluation of the full potential of a rugged semi-submersible as a low cost force multiplier for littoral mapping purposes in both commercial and military applications. Vehicle attributes include a notable sea-keeping capability that offers promise for nautical charting surveys, military applications, and homeland defense programs. This program builds upon earlier NRL research with the unmanned semi-submersible survey prototype, ORCA (Oceanographic Remotely Controlled Automaton) to support the Naval Oceanographic Office (NAVOCEANO). The ORCA was an air-breathing vessel with a majority of its structure traveling just below the water surface. The ORCAs radio antennae were affixed to a snorkel, which allowed for remote vehicle command and control in addition to real-time data transfer. The ORCA also used Differential Global Positioning System (DGPS) for precise positioning. In a similar fashion, the newly developed USS navigates submerged with only a narrow sail structure extending above the waterline. The USS design criteria are based upon the maximum integration of readily available Commercial Off The Shelf (COTS) hardware and instrumentation acquired largely from small boat technology. Requirements mandate a form factor suitable for stern ramp launch and retrieval, the capacity to operate dockside without special equipment, a re-configurable payload capability, a survey speed of at least six knots, and an endurance of at least two days. Overall vehicle height is restrained to allow for safe maintenance work on the deck of a moving ship and to accommodate shipping and storage within standard ISO containers. The USS program is aimed to provide risk reduction to support the Navy Unmanned Underwater Vehicle (UUV) Master Plan by evaluating new sensors, modularity, commonality of equipment, and experimentation with UUV systems. This paper discusses the USS concept, the decision making process, program milestones, and the vehicle design process including establishment of the performance criteria, hydrodynamic model testing, computer simulation, manufacture, and sea testing results.

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to rest. It was decided that the new vehicle should be designed to be operated for 2 to 4 days continuously before retrieving the vehicle for data recovery and refueling. The productivity of survey launches is also limited by the operational weather window. The data from the sonars become degraded when the wave heights are higher than about 0.7 meters and the operation of the boat becomes dangerous as the sea state increases. Survey operations can be shutdown for long periods of time due to rough weather. The new vehicle was designed to minimize the effect of waves on vessel motion. A goal is to have the vehicle capable of producing good quality sonar data in one to two meter seas while providing a safe operating environment for the crew.

Another goal of the project is to minimize the disadvantages of an autonomous vehicle. Specialized vehicles tend to have many custom designed components which are expensive, unreliable, and difficult to maintain. The designers of the new vehicle avoided the use of specialized equipment by using off-the-shelf parts where possible. The designs of each subsystem were kept simple in an attempt to reduce maintenance costs.

Most previous autonomous semi-submersible vehicles were difficult to launch and retrieve. The new vehicle was designed with a simple launch and recovery method in mind.

Initial Research

Several brainstorming sessions were held to try to come up with ideas for vehicles which would meet the design goals. Many designs were considered and the most promising designs had the bulk of the vehicle below the water with small surface expression to reduce the effects of wave action. Illustration 1 shows some of the concept hulls that were considered.

ASV Ltd of Chichester, England was contracted to help with vehicle design. ASV has built prototype vehicles similar to some of the concept hull designs. They also have extensive marine engineering expertise to complement C & C's operational experience.

AUVs have three major challenges when compared to surface vessels. The first challenge is maintaining sufficient main power. It was decided that an air-aspirated engine should be used for this vehicle to provide the large amount of power required and to have the desired duration. It was anticipated that the vehicle would run in shallow water and could run just below the water's surface allowing for an air intake for the engine. The second challenge is to provide high-accuracy real-time positioning. Since it was decided that the vehicle would have a surface expression it would be simple to install a survey-grade GPS to provide positioning data. The third challenge is communication. Again, the surface expression allows the use of high-speed broadband radio systems.

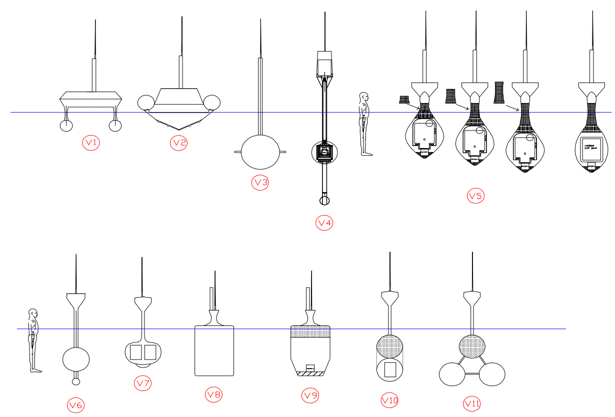

Illustration 1: Concept Hulls

All of the concept hulls fall into the categories of semi-submersible hull types and semi-floater hull types. Both hulls have the bulk of their volume below the water surface. The semi-floater would have a large cross-section of surface expression whereas the semi-submersible would have a small cross-section of surface expression.

Computer models were developed to predict the performance of each of the candidate hull concepts. The models estimated the roll, pitch and heave of each hull in varying sea states and varying wave periods. The stability results from all of the models were compared and the top three conceptual hulls were chosen for further investigation.

Physical scale models of the top three hull designs were constructed. The models were evaluated in a tow tank facility. The tests were conducted over a wide speed range in both calm waters and irregular seas. The best performing hull design was a semi-submersible concept. See illustration 2. That concept hull was modified and tweaked to optimize the model's performance in the test tank.

Detailed Design

Once the concept hull type was chosen attention turned towards engineering a detailed concept design. A goal in the detailed design phase was to improve upon known problems that had been experienced with previous semi-submersible vehicles.

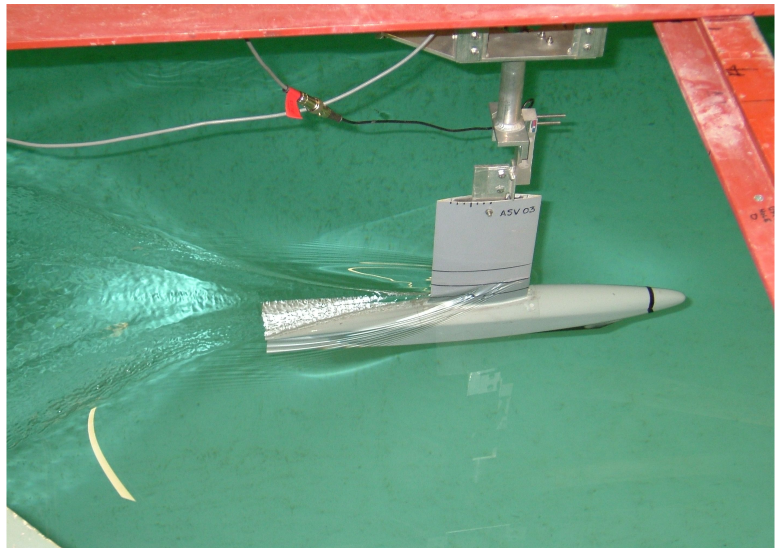

Illustration 2: Tow Tank Tests

One problem with some semi-submersible vehicles was that they were positively buoyant and pulled themselves underwater with active planes. The effect of the plane area limited the operational speed of the vehicle. A minimum speed was required to have sufficient authority to control depth and pitch and the maximum speed was partly limited by the frictional drag of the planes. It was decided that the USS vehicle would have a sail as a surface projection and would have a static draft with the keel always at the proper survey depth. The vehicle would have minimal planes for trim adjustment and a rudder.

Many semi-submersible vehicles are challenging to launch and recover. They have control planes and keels that protrude from the main body and are easily damaged by handling equipment. The attachment point for recovery are usually on the top of the vehicle near the mast and antennas making recovery in rough seas precarious. The planes and rudder on the USS are designed such that they do not protrude to the side or bottom of the vehicle but are behind the vehicle to minimize the chance of damaging the planes during launch and retrieval.

Although the USS was originally designed without a protruding keel, the final design included a minimal keel to maintain sufficient righting moment. The USS was also designed to have a releasable nosecone with towline attached. The front attach points are used to tow the vehicle up an articulated sled. This recovery system was chosen due to the great success that C & C has experienced with it over the years in towfish and AUV recovery.

Many issues were considered when deciding on the total size of the vehicle. Small size would best facilitate launch, recovery, and general deck handling of the vehicle. On the other hand, a larger vehicle would be more stable in rough seas, would have more room for fuel to enable a longer endurance, and would support hydrodynamics that would allow a higher top speed. An initial design was comleted making the vehicle as small as possible while still being able to carry the proposed initial suite of survey sensors. A flooded hull design was used to minimize size and weight. It was recognized that a vehicle optimized for the smallest size would not be sufficiently flexible to carry a wide range of future sensors so the vehicle design was extended from an initial 5.5 meters long to a final 6.3 meter length.

Commercial off-the-shelf (COTS) equipment was used wherever possible in the design of the USS. A popular three cylinder Yanmar diesel engine was chosen for the main propulsion. Most components are standard small boat technology supplies. The electronic control system is composed of common factory automation programmable logic controllers (PLCs). The use of COTS equipment ensures a plentiful supply of inexpensive, proven spare parts.

Fabrication

Illustration 3: USS Vehicle

The USS was fabricated by a joint team from C & C, ASV, and other subcontractors. The work was completed at ASV's Chichester facility.

The main components of the USS are the frame, sail, and keel. The frame, sail, and bottom skins are constructed from welded aluminum. The initial materials were designed as laser cut aluminum parts kits. The cut parts were fitted into a jig and welded together. The keel is a steel frame with poured lead for ballast. The upper body skins are made of foam flotation material. The sail is mostly hollow and contains a water separator for the engine air intake.

Initial Sea Trials

The initial sea trials were designed to validate the base vehicle. The main vehicle control computer and survey sensors were not installed. The servo systems were controlled by the PLC on the vehicle and the PLC was operated by remote control over a radio link from a remote control console.

The first sea trial was performed in southern England near Portchester. The USS was launched into the water with the aid of a truck mounted crane. The ballasting of the vehicle was verified. Basic engine and control functionality was verified by running the engine and making small slow maneuvers in a small closed docking basin. Most subsystems worked well but one major flaw was discovered. The engine was stopped and started again several times during various tests and one time, when the engine was stopped for an extended period of time while the USS was in the water, seawater intruded into one of the cylinders of the diesel engine. It was found that the valves in the cooling system were not sufficient to always prevent the flow of seawater into the wet exhaust when the engine was stopped. The valving system was modified to better control water intrusion.

The second second sea trial was done in Langstone Harbor near Portsmouth, England. The USS was launched by crane at the dock and towed out a safe distance into the harbor. Tests were done to verify basic vehicle control and emergency shutdown systems. The USS was exercised to evaluate the hydrodynamic performance of the system. The vehicle exhibited low friction loss and excellent speed at low engine RPM. Problems were found in the pitch stability of the vehicle at higher speeds (above about 6 knots) where it would dive too deep when perturbed by following seas.

Some quick experimental engineering changes were made to the USS to try to stabilize the pitch dynamics. Some foam sheets were attached to the sail increasing the cross-sectional area in an attempt to increase the draft correcting forces. An additional screw-adjustable static trim plane was added on the stern.

Illustration 4: USS in Docking Basin

The experimental changes were tested in a third sea trial. It was found that the additional trim fin had to be set at an angle of 35 degrees to keep the USS stable.

It was decided to ship the vehicle to C & C's Lafayette facility so that the control computer and survey sensors could be integrated. Simultaneously, the subcontractor in England would continue with model tests to help find an engineering solution to improve dynamic stability. A new scale model was constructed to more precisely match the actual constructed hull. The previous scale model was based on the 5.5 meter design of the USS. Late in the design, it was decided to extend the vehicle to 6.3 meters. Although the extra length was thought to have little effect on the hydrodynamics of the vehicle, the demonstrated pitch instability has proven the extra length is significant.

Vehicle Processor Sea Trial

The USS vehicle, trailer, and associated components arrived in Lafayette on 14 July 2009. The delivery was unpacked and inspected for damage. The only damage found was some compressed flotation foam on the top of the hull due to some overly tight tie-down straps.

The team worked on integrating the vehicle processor (VP) and primary vehicle sensors. The VP is the main control computer for the vehicle. It interfaces with the PLC to provide for the basic operations of the vehicle. The primary vehicle sensors are a Coda Octopus F-180 roll, pitch, heave, and heading sensor, an upward-looking altimeter, and a downward-looking altimeter. The VP communicates over a wireless Ethernet radio to the vehicle server (VS) and user interface (UI) on the mothership.

The belly pack and PLC programming were modified to support dual mode operations. The USS could be controlled with the belly pack communicating directly with the PLC on board the vehicle as was done for the sea trials in England, or, alternatively, the VP could be put in control of the PLC on the vehicle. The VP would always get all feedbacks and setpoint input from the vehicle and radio link. The dual mode system was implemented so that the VP could be tested, debugged, shutdown, modified, and restarted while the USS was underway during sea trials.

The USS was tested as much as possible in the shop. Each circuit, feedback, setpoint, servo system, and control was individually tested and verified. Each failsafe was activated and verified. The radios were operated and tested for cross-interference and minimum range. The engine and propulsion system were checked. The electrical power systems and charging circuits were checked. Everything that could be checked out of the water was verified.

Sea trials were executed from 5 August 2009 through 7 August 2009 out of Cameron, Louisiana. The USS and support trailer were loaded onto a flatbed truck and hauled to the dock at McCall Offshore Boats in Cameron. A crane was used to lift the USS and lower it into the water. Two C & C owned boats were used for support. The “Captain Blake”, a 12 meter Lafitte Skiff, was used as the mothership and the “Butte”, an 8 meter twin engine work boat, was used as a tow vehicle and tender.

Illustration 5: USS Sea Trial

The first procedure of the sea trials was to verify the ballast and trim of the USS. Mounting the VP electronics box and primary sensors on the vehicle affected the weight and buoyancy. Every effort was put into correcting for the changes but it was not possible to verify the corrections until the vessel could be immersed in seawater. The ballast was adjusted and re-tested.

On the second day of the sea trial, the vehicle was launched and exercised near the dock. All systems were operational except that the F-180 remained in calibration mode. The F-180 needs to run through a calibration process after a new installation so that it can determine the precise separation and offsets to the two differential aiding GPS antennas. The calibration requires that the platform move in various patterns so that the computers can statistically solve for the offset measurements.

It was decided to continue the sea trials while the F-180 was calibrating. The Butte towed the USS down the Calcasieu Ship Channel and past the jetties into open water in the Gulf of Mexico. The control functions of the VP were exercised and tested. Each of the feedbacks to the VP were verfied to be operating properly. The modified belly pack system was tested with no problems found. All of the functions worked well except for the heading control system.

The most complex function added to the USS was the heading control system. The heading control system is designed to control the rudder system such that it will maintain a commanded compass heading. The F-180 is the main compass on the USS and it would not complete its calibration phase. The USS was maneuvered in various patterns to help the calibration process, but no amount of maneuvering would get the process to complete. The heading control system could not be tested without a good operational compass.

The USS was towed back to the dock and recovered onto the support trailer. The F-180 setup parameters were verified to ensure that they were correct. A computer was connected to the F-180 so that the calibration process could be controlled and monitored. The trailer was hitched to a truck and towed in patterns around the parking lot to get the F-180 to complete calibration. After calibration completed, the real-time output of the F-180 was checked against other compasses at various headings to verify that it was working properly.

On the third day of sea trials, the USS was launched and subsystems were checked while the vehicle was near the dock. The output of the F-180 was checked and it had quickly completed its initialization and went into real-time output mode. After all the checks passed, the Butte towed the vehicle out the channel to the test area in open Gulf of Mexico waters.

The primary work in this part of the sea trial was to get the heading control system working. The control algorithms were tested and tuned but would attain only a slow wallowing heading near the commanded heading. More aggressive tuning of the initial algorithm would lead to instability. The algorithms were changed a few times and tuned many times until the vehicle would aggressively hold the commanded heading. The final algorithm worked well except that it would overshoot the commanded heading for long turns. It would overshoot by about 7 degrees in a 90 degree turn and overshoot about 20 degrees in a 180 degree turn. It was decided that this was acceptable performance to run survey lines. The team could continue to refine the algorithms during subsequent sea trials.

Conclusion

The sea trials have tested and verified most of the functions of the base USS vehicle (the truck) and identified issues to be addressed.

The propulsion system has been quite stable. The engine ran well and had good power. The cooling system maintained good engine temperatures. The engine feedbacks all worked well. The throttle control and transmission control both worked well. The fuel bladder and fuel system worked without a problem. The air intake system, water separator, and failsafe valve worked well. The wet exhaust system, water trap, and failsafe valve worked well after installation of a solenoid valve in the raw water injection line.

The power system has been working well. The 24 volt system has sufficient power to run all the installed equipment and quickly charge from the engine alternator. The 12 volt system is quickly recharged by the charging system running on the 24 volt primary system. The power distribution system and power controls have operated without problems.

The control systems are operational. The active planes move quickly and with good authority. The position feedbacks are accurate and reliable. The rudder has good authority for maneuvering.

The hydrostatics of the hull are good. The USS has a strong righting moment and floats at the designed draft.

There is still work to be done to improve the hydrodynamics of the USS. It works well at lower speeds (5.5 knots and below) with very little vessel motion induced by moderate seas but has problems with stability in pitch and draft at higher speeds. Work is ongoing to engineer changes to the hull and/or planes to provide for better dynamic stability at higher speeds.

The USS vehicle (the truck) is working well enough to proceed with sensor integration and sensor trials. Primary survey sensors, including a multibeam sonar system and a sidescan sonar, will be integrated into the vehicle along with a payload computer for control and data acquisition.

The next sea trial will be to prove the survey sensors. The goal will be to test and troubleshoot the newly installed survey sensors. Tests will be performed at speeds of 5.5 knots and below until changes to the hull have been implemented.